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16. ABSTRACT

Measurements of PM-10 particulate matter emissions from stationary sources were performed using two sampling approaches currently under development. PM-10 particulate matter is defined as all particles nominally 10 μm aerodynamic diameter and smaller. Aerodynamic inertial particle sizing devices are used in both approaches. The emission gas recycle (EGR) approach used new instrumentation and, as the duct sampling nozzle flow rate was adjusted to remain isokinetic, conditioned recycled emission gas was adjusted coincidentally and added prior to the sizing device: the combined recycle and sample flow at all sampling points in the traverses was the constant required by the sizing device. This satisfied the previous conflict of varying isokinetic flow and constant sizing device flow. The simulated Method 5 (SIM-5) approach used existing instrumentation and a new sampling protocol. Both approaches use multiple points in the sampling plane. At the three industrial sites the PM-10 concentrations ranged from 3 to 800 milligrams per dry standard cubic meter (mg/DSm^3), while total particulate mass was from 15 to 4000 mg/DSm^3. EGR and SIM-5 compare favorably with each other and with the reference measurements at the sites.

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Introduction

PM-10 particulate matter concentrations were measured in stack gases which passed through selected sampling planes in ducts at stationary sources. The United States Environmental Protection Agency (USEPA) has defined PM-10 particulate matter[1] to include all particles with aerodynamic diameters nominally 10 micrometers (μm) and smaller. Samples were taken before and after control devices. The duct gases contained PM-10 particulate matter concentrations ranging from 3 to 800 milligrams per dry standard cubic meter (mg/DSm^3) and total particulate matter concentrations from 15 to 4000 mg/DSm^3.

These measurements were made as part of a program by the Environmental Monitoring Systems Laboratory, USEPA, to initiate, develop, and evaluate stack gas sampling methodology for PM-10 particulate matter in stationary sources. Because no established methodology existed prior to this work, and because of the potentially wide range of expected concentrations to be measured, two sampling methodologies were initiated and are being evaluated. Both were used in performing these measurements. One is the Emission Gas Recycle (EGR) method. The EGR method used the Emission Gas Recycle Train[2,3] developed in this program and the procedures for its use in stack gas PM-10 particulate matter measurement. The other is the Simulated Method 5 (SIM-5) method. The SIM-5 method used existing instrumentation with specific procedures required by the sampling protocol[4] developed in this program. Both methods are designed to produce a representative measurement of PM-10 particulate matter in the duct gases by sampling at multiple points in the sampling plane.

Sampling Methodology

Since PM-10 particles[1] are defined by their aerodynamic diameters, inertial particulate sizing devices which classify particles according to their aerodynamic size are used in both the EGR and SIM-5 methods. These inertial devices are operated in-stack to eliminate potential sized-particle measurement errors caused by particle losses in a long probe or other sample transport lines. After the PM-10 particles are separated aerodynamically from the sampled gases, they are analyzed gravimetrically. Using the mass of PM-10 particulate matter and the volume of duct gases from which it was taken, the concentration of PM-10 particles is determined. From the measurement of the total duct gas flow through the sampling plane and the PM-10 concentration, the PM-10 mass flow rate may be calculated. This PM-10 mass flow rate is by definition the source emission rate when the sampling plane is selected properly in the duct gases not subjected to further control or removal of particulate matter. These two PM-10 methods are more complicated than USEPA Method 5 because of the following reasons: (1) the more complicated EGR train and its operation; (2) the greater care necessary during the taking and weighing of the size-classified samples compared to the total-mass samples of Method 5; and (3) the more complicated calculations required prior to beginning the sampling traverse for proper operation of

the trains. However, except for the instrumentation and the specifically different procedures[2,4] by which the PM-10 sized sample is produced, the methodologies to measure the PM-10 mass flow rates are very similar to the USEPA Method 5 methodology for measuring total mass flow rates.

Cascade impactors[4] and small sampling cyclones[2,4] were the inertial sizing devices used in the two methods. The internal flow rates must be held constant within these and other similar inertial sizing devices for a given set of gas parameters to maintain constant particle-size separation at the desired PM-10 cutpoint.

The EGR method is designed to satisfy the heretofore conflicting requirements of coincidental isokinetic sampling and constant flow rate through the sizing device throughout a traverse of a typical stationary source sampling plane as required by Method 1. The EGR design allows a controlled, variable flow of filtered, conditioned and recycled emission gases to be combined with the duct sample after the acquisition of the duct sample by the sampling nozzle, but prior to the sizing device in the train[2,3]. The flow rate into the sampling nozzle is selected and controlled at each point of the traverse to be isokinetic with the duct velocity at that sampling point; coincidentally, the recycle gas flow rate is selected and controlled to cause the combined (sample and recycle) flow rate to be a constant value. This combined flow rate is a constant value throughout the traverse and is equal to the flow rate required by the sizing device to produce the desired PM-10 cutpoint[2,3].

The SIM-5 method is designed to allow a constant inertial sizing device flow rate and a constant nozzle flow rate throughout the 8 to 12 point sampling traverse. First the desired flow rate is calculated for the sizing device. An acceptable sample is obtained by management of PM-10 sampling conditions at acceptable levels by keeping the sampling rate of the nozzle within a stated fraction of isokinetic[4]. This often requires only one nozzle, but it may require use of more than one nozzle per traverse. When only one nozzle is required for the full traverse, it is selected to satisfy coincidentally both the following criteria: 1. the flow rate required by the sizing device, and 2. the isokinetic velocity (or as close as possible) corresponding to the point of average velocity in the traverse. Sampling time per point is calculated to yield a volume proportional to the duct velocity at the point. When more than one nozzle is required, a subset of points for each nozzle to be used is selected from the total set of points in the full traverse. Each subset is then sampled by its nozzle in the same manner described above for the full traverse. Since the set of points sampled in the subsets is exactly the same as the set of points in the full traverse, the results of each subset are combined to yield the desired total.

Description of Field Sites and Tests

Field sampling sites were selected to provide evaluation of the EGR and SIM-5 methods in a wide range of PM-10 particulate matter concentrations

in stack gases. Tests were performed in sampling planes in ducts from coal-fired boilers at three utility electric power-generating stations. Table I shows the range of PM-10 and total particulate matter measured at the sites. Table II shows the PM-10 methods and train configurations used at the test sites. The EGR method was operated with a cyclone[2], while the SIM-5 method[4] was operated with a cyclone or an impactor.

The focus of this paper is evaluation of the methods based upon sampling the full number of points required in the traverse by the EGR and SIM-5 methods. These full traverse samples are the best approach which allows evaluation of the methods precisely as developed for measurement of PM-10 particulate matter in stationary sources. However, reduced point tests are cost effective in evaluation of many aspects of multiple-point sampling methods. Therefore, tests were performed, also, using reduced numbers of points in the traverse. Data from the reduced traverse tests are shown only for the purpose of indicating PM-10 fractions of total mass concentrations during the measurements. Data from the reduced traverse tests are discussed in detail in separate reports[3,4]. Reference emission data were produced independently for comparison to the EGR and SIM-5 data. The reference data were produced by sampling with one to four impactors at a time at many or all of the individual points of the PM-10 methods, and by sampling with a Method 17 type total particulate mass train. The reference trains were run: (1) collocated (same point, same time) with the PM-10 trains when possible, (2) in the same sampling plane at the same time as the PM-10 trains but not collocated, and (3) as close in time as possible and in the same sampling plane as the PM-10 trains, typically beginning within 1/4 to 4 hours after completion of the PM-10 train runs. These reference trains used University of Washington Mark V Cascade Impactors (UW5) or Method 17 equipment.

During tests at field site 1, the boiler was operated to produce a constant production rate of 28 megawatts (MW) out of a rating of 56 MW. The combustion gases were controlled by passing through an activated electrostatic precipitator (ESP) and were then sampled from a sampling plane 22 meters (m) by 6m. Duct gas velocities ranged from 8 to 23 meters/sec (m/s) and temperatures were 140 to 155°C. The mass median diameter (MMD) of particulate emissions averged 30 μm. A modified Method 17 type mass train for reference purposes was colocated with the full 12 point traverses of the SIM-5 (impactor) sampling train. In the same sampling plane at the same time, Method 17 reference train samples were taken at a 50 sampling points traverse. Reduced traverse tests were run, also.

During tests at field site 2, the boiler was operated to produce a constant full-load production rate of 250 MW. The combustion gases were controlled by ESP control devices, and were sampled in a duct approximately 5m by 3m. Duct gas velocities ranged from 9 to 30 m/s and temperatures were 130 to 145°C. The MMD of emissions averaged 10 μm. Only reduced traverse tests were run.

During tests at field site 3-INLET, the boilers were operated to produce a constant full-load production rate of 221 MW. Combustion gases were sampled prior to particulate control in an inlet duct 5m by 3m. Duct gas velocities ranged from 11 to 20 m/s and temperatures were 120 to 143°C. The MMD of the inlet particulate matter averaged 35 μm. Full 12 point traverses of the EGR and SIM-5 (cyclone) methods were taken in the same sampling plane in the same time frame but not co-located. Following each of the concurrent EGR and SIM-5 tests just described, an independent reference size distribution test was performed, with four concurrent UW5 cascade impactors sampling at 3 different points each to produce the reference value at the twelve points. Method 17 reference train samples were taken.

At field site 3-OUTLET, the combustion gases were first controlled by a baghouse and then ducted to a stack. Tests were performed at the 70m level of the stack in a sampling plane 6m in diameter. Duct gas velocities ranged from 13 to 18 m/s. The MMD of the outlet particulate matter was approximately 35 μm. Full eight point SIM-5 (impactor) traverses were taken. Method 17 reference train samples were also taken.

Test Results and Discussion

Tables III through VII show concentrations of PM-10 and total mass for all tests. Confidence intervals are given for the average of each measurement method.

Table III shows the difference in total mass concentration of the SIM-5 from the Method-17 traverse at site 1, along with 95% confidence intervals. The observed differences are not statistically significant at the 95% confidence interval for the mass concentration because temporal variations obscure the differences. Table IV shows reduced traverse data from site 1, and Table V shows reduced traverse data from site 2.

The differences of impactor results from each of the SIM-5 and EGR measurements at site 3-INLET are given in Table VI, along with 95% confidence intervals. The difference between EGR and SIM-5 are presented, also. The total mass concentration data suggests differences in the methods. However, the magnitude of the observed differences is not statistically significant at the 95% confidence level because temporal variations obscure differences, except the Method 17 to impactor data where Method 17 is expected to produce the more accurate total mass measurement. The PM-10 concentration data in Table VI does show significant differences in the techniques. The 11% difference observed between SIM-5 and EGR is significant at the 95% confidence level. Larger differences were observed between impactor and the EGR and SIM-5 methods. These differences may be due to differences at this site between the impactor and the cyclones of the EGR and SIM-5 trains. This supposition is supported by consideration of the PM-10 fraction data in which both the SIM-5 and EGR show a 21% fraction while the impactor shows a 15% fraction. This 6% difference between PM-10 fractions is statistically significant because 95% confidence intervals of the 6% difference were ± 2%.

Data for the site 3-OUTLET are presented in Table VII. These data show excellent agreement between SIM-5 and Method 17. The run times for the SIM-5 tests were approximately four times as long as those for Method 17. Longer run times normally minimize temporal variations, and this likely explains the larger 95% confidence intervals for the Method 17 compared to SIM-5.

Data from these tests show a PM-10 portion of the total mass emissions of 20% at two sites and 50% at one site (the site 3-INLET data are not considered here because the gases from which they were taken were subjected to a control device after being sampled). The number of sampling sites in these tests are limited compared to all stationary sources, and many sites could be expected to have PM-10 fractions outside these ranges.

Conclusions

Both EGR and SIM-5 methods are reasonable procedures for measuring PM-10 particulate matter flow rates in stationary source stack gases. By adapting the SIM-5 approach for use with a cyclone and an impactor, it has been used to sample in an extremely wide range of PM-10 and total mass concentrations, including before and after control devices. The EGR should be adapted for use with an impactor to extend its sampling capability similar to the SIM-5 method. Although similar in many aspects to USEPA Reference Methods 5 and 17, each PM-10 method is more complicated than the reference methods. At this stage of evaluation, neither PM-10 method can be determined to have significant advantage over the other.

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Discussion within this paper of sampling methodologies does not necessarily imply agency endorsement of these methodologies.

Table I. Range of PM-10 and Total Mass Concentrations in Duct Gases, mg/DSm^3

Site	PM-10 Particulate Matter	Total Particulate Matter
1	100	2,000
2	100	200
3-INLET	800	4,000
3-OUTLET	3	15

Table II. Methods with Sizing Devices Used at Test Sites

Site	EGR	SIM-5
1	EGR (Cyclone)	SIM-5 (Impactor)
2	EGR (Cyclone)	SIM-5 (Cyclone)
3-INLET	EGR (Cyclone)	SIM-5 (Cyclone)
3-OUTLET	---	SIM-5 (Impactor)

Table III. PM-10 Tests, Total Mass Concentrations at Site 1, Full Traverses

Method	Replicates	Total Mass Concentrations mg/DSm^3	95% Confidence* Intervals, mg/DSm^3
SIM-5	3	310	± 302
[Meth-17; Co-located with SIM-5]	3	356	± 295
Meth 17	3	372	± 415
Differences			
Meth 17 - SIM-5	3	61	± 123

* 95% Confidence Limit = $\frac{\sigma}{\sqrt{N}} \times t$

where σ = standard deviation

N = number of replications

t = student t factor

Table IV. PM-10 Tests, Concentrations at Site 1, Reduced Traverses

PM-10	Replicates	PM-10 Concentrations mg/DSm^3	95% Confidence Intervals, mg/DSm^3
SIM-5	4	105	± 53
Impactor	4	107	± 36
Differences			
Impactor - SIM-5	4	+1.8	± 23
Total Mass			
SIM-5	4	514	± 599
Impactor	4	593	± 461
Differences			
Impactor - SIM-5	4	75	± 353

Table V. PM-10 Tests, Concentrations at Site 2, Reduced Traverses

PM-10	Replicates	Concentrations mg/DSm^3	95% Confidence Intervals, mg/DSm^3
Impactor	6	103	± 22
SIM-5	7	107	± 20
EGR	7	92	± 23
Differences			
Impactor - SIM-5	5	-5.3	± 21
Impactor - EGR	5	7.7	± 19
Total Mass			
Impactor	6	193	± 49
SIM-5	7	221	± 51
EGR	7	202	± 47
Differences			
Impactor - SIM-5	5	-28	± 44
Impactor - EGR	5	-12	± 41

Table VI. PM-10 Tests, Concentrations at Site 3-INLET, Full Traverses

PM-10	Replicates	Concentrations mg/DSm^3	95% Confidence Intervals, mg/DSm^3
Impactor	5	613	± 102
SIM-5	6	716	± 69
EGR	6	803	± 90
Differences			
Impactor - SIM-5	-	-103	± 105
Impactor - EGR	-	-156	± 106
SIM-5 - EGR	6	-87	± 74
Total Mass			
Impactor	5	4022	± 444
SIM-5	6	3590	± 444
EGR	6	3648	± 547
Meth 17	11	3077	± 702
Differences			
Impactor - SIM-5	-	432	± 533
Impactor - EGR	-	374	± 602
SIM-5 - EGR	6	-58	± 722
Meth 17 - Impactor	-	-945	± 758
Meth 17 - SIM-5	-	-513	± 766
Meth 17 - EGR	-	-571	± 810

Table VII. PM-10 Tests, Concentrations at Site 3-OUTLET, Full Traverses

PM-10	Replicates	Concentrations mg/DSm^3	95% Confidence Intervals, mg/DSm^3
SIM-5	10	2.9	± 0.28
Total Mass			
SIM-5	10	14.5	± 0.9
Meth 17	7	15.6	± 3.6
Differences			
Meth 17 - SIM-5	7	1.1	± 3.3

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